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WIND TUNNEL WALL INTERFERENCE

D.B. Bliss

PRINCETON UNIVERSITY

Department of Mechanical and Aerospace Engineering

November 1980

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The previous analysis of the aerodynamics of an isolated slender slot in a wall has been extended to include the effect of a streamwise pressure gradient. For certain slot planforms, an analytical solution is available for the case of a linear pressure gradient. The effect of aerodynamic interference for a single infinite row of slots was also studied. Solutions were obtained numerically for various Mach numbers, slot spacings, and aspect ratios. The effect of interaction between slots was to increase slot flow rate for a given pressure differential. A wavy wall problem was posed (con't)

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to study the proper method of obtaining an averaged wall boundary condition given the behavior of individual holes or perforations. This problem contains all the important physics and allows the basic parameters to be controlled in such a way that the important efforts can be clearly identified. Due to computational difficulties, the solution is being reformulated in a more efficient and useful form. However, preliminary calculations with the original approach did show that the boundary condition should be constructed differently for subsonic and supersonic flows, and that there are effects of pressure gradient and hole location become apparent as the pressure field wavelength is decreased. Some work was also done on isolated slot aerodynamics with large free surface displacement and on the compliant wall wind tunnel concept.

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I. Summary and Current Status

During the past year research was conducted on several topics related to wind tunnel wall interference. In subsequent sections of the report this research and the relevant background information are described. In particular, Section V describes the work done during the past year. The work on the effect of pressure gradient on an isolated slot and on the interference between a row of slots is essentially complete. This work will be the subject of a technical note submitted for publication within the next few months. Some technical difficulty was encountered in the development of averaging methods for perforated walls, perhaps the most important aspect of this research program, but a way to resolve the difficulty has now been found.

The major technical progress during the past year is summarized as follows. The previous analysis of the aerodynamics of an isolated slender slot in a wall has been extended to include the effect of a streamwise pressure gradient. For certain slot planforms, an analytical solution is available for the case of a linear pressure gradient. The effect of aerodynamic interference for a single infinite row of slots was also studied. Solutions were obtained numerically for various Mach numbers, slot spacings, and aspect ratios. The effect of interaction between slots was to increase the slot flow rate for a given pressure differential. A wavy wall problem was posed to study the proper method of obtaining an averaged wall boundary condition given the behavior of individual holes or perforations. This problem contains all the important physics and allows the basic parameters to be controlled in such a way that the important efforts can be clearly identified. Due to computational difficulties, the solution is being reformulated in a more efficient and useful form. However, preliminary calculations with the original approach did show that the boundary condition should be constructed differently for subsonic and supersonic flows, and that there are effects of pressure gradient and hole location become apparent as the pressure field wavelength is decreased. Some work was also done on isolated slot aerodynamics with large free surface displacement and on the compliant wall wind tunnel concept.

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II. Overview of the Problem

Wind tunnel wall interference is an issue of renewed concern due to the need to use larger models to achieve high Reynolds number and due to the importance of obtaining accurate results at transonic speeds, where interference is most severe. Solid wall wind tunnels tend to increase lift while open jet wind tunnels decrease lift as compared to that of a model in a free field. At transonic speeds the flow is very sensitive to area changes and severe blockage effects can occur. At transonic and low supersonic speeds shock reflection from the wind tunnel wall can also cause serious interference. It has long been recognized that ventilated (slotted or perforated) wind tunnel walls can significantly alleviate many of the interference problems just mentioned.

A recent potentially important development is the so called intelligent wall wind tunnel concept.[1] The flow rate through ventilated walls is controlled as a function of location along the wall by external means. Flow quantities are measured at stations near the wall and adjusted in an attempt to simulate free field conditions, and thereby eliminate, or at least minimize, wall interference. Another increasingly common approach is to use a conventional ventilated wall tunnel and make supplementary flow measurements near the walls.[2] Interference corrections can then be made on the basis of the actual state of the flow near the wall. The difficulty with this approach is that a large number of additional measurements may be required and the complexity of the experiment is increased. The advent of new approaches to the wind tunnel wall interference problem has increased, rather than diminished, the need to understand the basic physics of the flow near a ventilated wind tunnel wall.

The reason such approaches are deemed necessary is that our understanding of the fluid mechanics of slotted or perforated walls is imperfect. The design of ventilated walls is in fact largely empirical.

Equivalent homogeneous boundary conditions have been proposed for various wall geometries. This approach seems reasonable provided that the number of slots or perforations is sufficiently high that it is meaningful to speak of an average behavior of the wall surface. The boundary conditions involve certain coefficients reflecting the average wall properties, for instance a perforated wall is characterized by an effective porous wall flow resistance. However, the experimental determination of these coefficients and the actual application of the boundary condition has not always lead to satisfactory results.

Fundamentally, the wall boundary condition depends on the aerodynamics of the individual elements that make up the wall (slots or holes) and on the aerodynamic interference between these elements within the region over which the averaging takes place. Although wall boundary conditions have received considerable attention many basic issues remain unresolved. The work performed during the past year addresses a number of these issues as they pertain to both slotted and perforated walls. Both the aerodynamics of wall elements and the interference between wall elements were studied.

III. The Wind Tunnel Wall Boundary Condition

Generally, both slotted and perforated walls have been represented by a homogeneous boundary condition of the form[3,4]

$$\phi_x + K_p\phi_z + K_s\phi_{xz} + K_H\phi_z^2 = 0 \qquad (1)$$

where ϕ is the velocity potential, x is the streamwise coordinate, z is the coordinate normal to the wall, and K_p, K_s, K_H are coefficients which depend (at least) on wall element geometry and Mach number. The first term on the left is associated with the perturbation pressure; the second term is like an effective flow resistance due to normal flow, the third term is assoicated with streamline curvature; and the last term is a non-linear pressure drop associated with flow separation. Depending on the type of wall element, different terms in the boundary condition are important[4]. For instance, the flow resistance coefficient K_p is much larger for holes or perforations (aspect ratio ~ 0 [1] than for slender slots (aspect ratio << 1); the streamline curvature term is most important for slender slots.

Considerable theoretical and experimental work has been done to determine the coefficients in Equation (1) for slender slots.[3-8] The theoretical work has typically involved the use of slender body theory. Analytical formulae have been proposed for the streamline curvature coefficient, K_s, and the nonlinear pressure drop term, K_H, for a wall covered with a row of streamwise slots. An analytical expression for the linear flow resistance coefficient, K_p, when the slot is tapered has also been proposed. These results have not been systematically reconciled with experiment. For instance, experiments show a linear flow resistance behavior even for untapered slots. This issue, which is discussed further in the next section, was resolved under a previous AFOSR grant, but it reflects on the general state of understanding of this problem.

For perforated walls, the fluid mechanics of the flow through the individual holes appears to be very complex, particularly if the hole aspect ratio is of order unity and if the wall thickness is comparable to the hole diameter, which is often the case. Given the difficulty of analyzing a high speed impinging separated flow, the flow resistance coefficient, K_p, is usually determined experimentally.[8] The holes are sometimes shaped or angled to give a certain desired behavior. The problem is that the experimental determination implictly assumes that for a given wall geometry K_p depends solely on Mach number. In fact, K_p may very well depend on the relative size of the length scale of an applied pressure disturbance and the slot spacing. The effect of gradients on the averaging procedure and the determination of K_p is an issue which deserves further study. It is necessary to re-examine the basic form of the boundary condition Equation (1) based on a better understanding of the important effects.

IV. Aerodynamic Behavior of a Slot

In previous work supported by AFOSR the aerodynamics of an isolated finite length slender slot in an infinite wall beneath a uniform high speed flow has been investigated[10]. This analysis was undertaken because it is important to understand the behavior of a basic wall element in isolation before considering a wall made up of many elements. Furthermore, it was felt that an apparent discrepancy between the previously proposed theoretical boundary condition [4,5,6] on a slotted wall and experimental measurements could be resolved. Experimental measurements show a linear behavior between pressure drop and flow rate when the flow into the slot is small, even when the slot is untapered and allows only a streamline curvature term associated with disturbances in the free stream[4]. In the notation of Equation (1), $K_p = 0$ and $K_s \neq 0$.

A theoretical model of the flow through a single finite length slot was constructed using slender body theory.[10] The inner solution is found to be a two-dimensional crossflow in the vicinity of the slot governed by Laplace's equation. The outer solution is a line of sinks in the compressible flow field. Two limiting cases were considered: small free surface deflection corresponding to a small pressure differential across the slot; and large free surface deflection (fully developed crossflow) due to a large pressure differential.

The analysis shows that the magnitude of the crossflow at any point is significantly affected by the crossflow at other points along the slot. This effect is caused by the outer solution which involves the sink strength distribution in the streamwise direction. The problem formulation leads to an integral equation as a consequence of this interaction. The interaction between points on the slot also restricts the circumstances under which a slotted wall can be represented by a point boundary condition.

The analysis shows that the previously mentioned linear behavior will arise even when the slot is not tapered. Physically, the linear behavior is associated not only with slot taper but also with the region downstream of the leading edge where the free surface flow is beginning to form, but has not reached its final crossflow configuration as an orifice or jet flow. If the mean flow through the slot is small, the crossflow never reaches its where the slot planform thickness, t(x), is given by

$$t(x)_{\text{subsonic}} = \frac{\ell n\ 16}{\ell n\left[\dfrac{4\ell^2}{x(\ell-x)}\right]}\ ,\ A_f = 0.848 \qquad (4)$$

and

$$t(x)_{\text{supersonic}} = \frac{\ell n 16}{\ell n\left[\dfrac{16\ell^2}{x^2}\right]}\ ,\ A_f = 0.677 \qquad (5)$$

The subsonic slot is symmetric with very blunt ends; the supersonic slot is not symmetric but has a very blunt leading edge and a truncated trailing edge. A recent important extension of the analytical solution is described in the next section.

An approximate solution for an untapered slot with a fully developed crossflow was also obtained with end effects being neglected. The result shows the quadratic behavior when the slot is subjected to a large pressure differential:

$$\frac{\Delta p}{q} = \frac{1}{\sigma^2}\left(\frac{w_m}{U}\right)^2 \qquad (6)$$

where σ is the ratio of the final width of the separated jet flow leaving the slot to the slot width ($0.6 < \sigma < 1.0$, depending on the nature of the flow separation process).

Quantitative comparison of these results with the limited available experimental data showed good agreement in both the regions of linear and quadratic behavior.

fully developed state and the linear term dominates. When the mean flow is large most of the crossflow resembles a fully developed separated orifice flow and the quadratic term dominates.

For small free surface displacement the linear behavior of the slot can be expressed as

$$\frac{\Delta p}{q} = \frac{a}{\ell} A_f G \frac{w_m}{U} \tag{2}$$

where

Δp = pressure differential applied across the slot

q = dynamic pressure

w_m = average normal velocity into slot

U = free stream velocity

a/ℓ = slot width to length ratio

A_f = area factor (area = $A_f a\ell$)

G = slot flow coefficient (function of a/ℓ and Mach number M)

The coefficient G was determined by a numerical solution of the governing integral equation for a family of slot planforms in subsonic and supersonic flow.

Of special interest was the discovery of a simple analytical solution for certain slot planform shapes. The solution is

$$G = \frac{4}{\pi} \left\{ \ell n \left[\frac{4\ell/a}{\sqrt{|1-M^2|}} \right] - 1 \right\} \tag{3}$$

V. Progress During the Past Year

In this section the research activity during the past year is summarized according to topic.

Effect of Applied Pressure Gradient

The solution described earlier for the flow through an isolated slot has been extended to include the effect of an applied pressure gradient due to a disturbance flow. Such a disturbance would be caused by the presence of a model in the tunnel. The effect can be analyzed for an arbitrary pressure field acting in an arbitrary slot planform in either subsonic or supersonic flow. Of special interest, however, is the existence of an analytical solution when a constant pressure gradient (linear streamwise pressure variation) is applied to the special slot planforms for which analytical solutions were previously found. The result gives a new form for the factor G in Equation (2):

$$G = \frac{2}{\pi} (A-2) \left[1 - \left(\frac{\partial C_p}{\partial x}\right) \frac{2\ell}{3C_p} \frac{(A-1)}{(A-3)} \right]^{-1} \tag{7}$$

where

$$A = 2 \ln \left[\frac{4 \ \ell/a}{\sqrt{|1-M^2|}} \right] \tag{8}$$

and $\left(\frac{\partial C_p}{\partial x}\right)$ is the constant pressure coefficient gradient. The slot planforms to which this applies are given by Equations (4) and (5) for subsonic and supersonic flow, respectively. It appears that analytic solutions are also obtainable for quadratic and even higher order streamwise pressure variations, but the algebraic complexity of the expression for G increases dramatically.

The constant pressure gradient result of Equation (7) is directly applicable to determining the effective flow resistance coefficient, K_p, in Equation (1) when the wall elements have small aspect ratio but their streamwise length is still short compared to the model. The streamwise pressure variation along the wall can then be approximated as locally linear over the length of any one element. The coefficient K_p would depend on pressure gradient as a consequence of the behavior of the individual slot elements. The aerodynamic interference between elements may also lead to a pressure gradient dependence as discussed later, so this result is also important to the understanding of interference effects.

Effect of Multiple Slots

The original analysis of flow through an isolated slot has been extended to apply to a wall covered with regularly spaced finite length slots. The flow over the wall is assumed to be uniform in the absence of the slots, i.e. there are no pressure disturbances associated with the presence of a model. Thus, all the slots behave identically. Nevertheless, the result is of interest because it shows the basic interference effect between slots. It also approximates an empty wind tunnel or a test plate with many slots, the arrangement sometimes used to determine the basic properties of a field of wall elements.[9]

To account for multiple slots the outer solution in the original isolated slot analysis is modified. It is not possible to find simple analytical solutions in this case, so numerical calculations have been made using a modification of the previous numerical procedure. The approach assumes the multiple slot effect is contained in the outer solution alone, which means the spacing between slots must be large compared to the slot width. This restriction should not be serious in practice.

In the classical treatment of the slotted wall boundary condition[4], which considers an infinite row of slots, what would be called the inner and outer problems are structured differently. The inner problem involves the crossflow through the entire row of slots and the outer problem is a vertically deflected free stream. This corresponds to the slot spacing comparible to, or smaller than, the slot width unless the slots are very long compared to both these dimensions.

Calculations have been performed for a single infinite row of parallel slots. The relevant physical parameters are the flow Mach number, the slot aspect ratio and normalized planform shape, and the spacing between slots. The governing integral equation now contains the effect of the other elements in the slot row. The primary physical effect of the other slots is to alter the local pressure differential which drives the flow through the slot. The integral equation must be solved by iteration, as with the isolated slot case. To simplify the iteration procedure and improve convergence the slot planforms were used for which analytical solutions were previously obtained (see Equations (4) and (5)). To reduce computer time in the subsonic case, an analytical far field approximation was used to account for distant slots. In this approximation, the spanwise summation for distant slot elements is replaced by an integral which can be evaluated directly. However, integration in the streamwise direction must still be performed numerically as part of the iteration procedure.

In subsonic flow, the integral equation becomes:

$$\frac{1}{\bar{w}t(x)}\bar{S}'(x) = \frac{x}{2} + C_1 + \frac{\bar{S}'(x)}{2\pi}\ \ell n\left[\frac{\varepsilon^2\beta^2}{4x(x-\ell^*)}\right] - \frac{1}{2\pi}\int_0^{\ell^*}\frac{\bar{S}'(x_1) - \bar{S}'(x)}{|x-x_1|}\,dx_1$$

$$-\frac{1}{\pi}\sum_{\eta=1}^{N}\int_0^{\ell^*}\frac{S'(x_1)dx_1}{\sqrt{(x-x_1)^2 + \beta^2 n^2 d^2}} \tag{9}$$

$$+\frac{1}{\pi\beta}\int_0^{\ell^*}\bar{S}'(x_1)\ \ell n\left\{\frac{1}{2} + \frac{1}{2}\sqrt{1+\left[\frac{x-x_1}{\beta(N+1)d}\right]^2}\right\}dx_1$$

where

$$C_1 = \frac{1}{\pi}\int_0^{\ell^*}\bar{S}'(x_1)\left\{\frac{1}{2x_1} + \sum_{\eta=1}^{N}\frac{1}{\sqrt{x_1^2 + \beta^2 n^2 d^2}}\right.$$

$$\left. + \frac{1}{\beta}\ \ell n\left\{\frac{1}{2} + \frac{1}{2}\sqrt{1+\left[\frac{x_1}{\beta(N+1)d}\right]^2}\right\}\right\}dx_1 \tag{10}$$

is chosen such that $\bar{S}'(0) = 0$. This equation corresponds to Eq. (43) of Ref. 10 for an isolated slot. In Eq. (9) the second line on the right hand side is the effect of N discrete slots separated by spacing d on each side of a central slot. The third term is the far field correction which accounts for slots further away than Nd. There is a similar equation for supersonic flow. However, because only a finite (usually relatively small) number of slots can affect the central slot due to the Mach cone angle, a far field correction is not required. The upper limit of integration now depends on the Mach number when computing the effect of the other slots.

In the subsonic case, it became more difficult to obtain convergence as the slot spacing was decreased or the Mach number was increased, and as the aspect ratio was decreased. The first and second trends tend to increase the aerodynamic interferences, whereas the third causes convergence problems even for an isolated slot. The supersonic case always converged easily. The results presented in Fig. 1 show the effect on $A_f G$ of slot spacing and aspect ratio for different Mach numbers. The quantity $A_f G$ is the basic proportionality constant between pressure differential and flow rate, see Eq. 2. The interference between slots has the effect of increasing the flow rate through the slots for a given pressure differential, as compared to the isolated slot. Figure 2 shows the change in $A_f G$ due to multiple slots normalized by the spacing to length ratio. In this case there is some degree of collapse of the calculated results, but probably not enough to justify the use of a simple porosity type correction for interference effects.

Fully Developed Slot Crossflow

The work described under the two preceding headings applies when the displacement of the free surface is small compared to the slot width. Another case occurs when the free surface displacement is large so that the crossflow in the slot resembles a fully developed separated orifice flow. The pressure versus flow rate relationship for a finite length slot is nonlinear. For a wall composed of slots with fully developed crossflow the boundary condition Equation (1) would be essentially a balance between the pressure term and the nonlinear term (the first and forth terms). This case was analyzed for a single finite length slot neglecting end effects as part of the research effort during the previous year.[10] This year some work was done to include end effects. A nonlinear integral equation was formulated but a numerical solution has not been attempted. Some further simplifications in this formulation may be possible since there is reason to believe, on physical grounds, that the end effects correction should be small when the crossflow is fully developed. More attention should be given to this problem in the future.

Averaging Methods for Perforated Walls

It is generally agreed that a perforated wall of sufficiently high hole density can be approximated by an equivalent porous wall. Exactly how the effective flow resistance of the porous wall should be determined, either theoretically or experimentally, is not sufficiently well understood and apparently has not been studied carefully. In an ongoing research effort, this very important question is being studied through the use of a wavy wall problem. Inviscid, irrotational, compressible flow passes between an impervious wavy wall (simulating a model) and a flat perforated or porous wall (simulating the wind tunnel wall). The goal is to find the porous wall boundary condition which most accurately reproduces the effect of the perforated wall on the wavy wall pressure distribution.

The perforated wall is represented as an array of identical holes (sources or sinks). The proportionality between flow rate and pressure difference for a single hole in isolation is assumed to be known and forms the basic building block for the analysis. The aerodynamic interference between the holes is determined when the array of holes is analyzed. This interference is of primary importance in determining the effective flow resistance coefficient in the equivalent boundary condition. The interference depends on the hole density, the imposed pressure gradient, and the Mach number. (Viscous effects, although possibly important, are not being considered).

The advantages of studying the wavy wall problem are that it is relatively simple analytically, all the potentially important physical effects are present, and the important parameters are easily identified and controlled, e.g. the pressure gradient is determined by the wall wavelength. The use of the characteristics of an isolated hole as the fundamental building block allows the contributions due to the basic hole and the aerodynamic interference between holes to be identified and separated. The separation of these effects may also prove to be a useful concept in the determination of an effective wall boundary condition from experimental data.

In the wavy wall problem at a particular Mach number it is of interest to know to what extent the effective flow resistence of the wall depends on s/λ and s/H. Here s is the distance between holes, λ is the wall wavelength, and H is the separation between walls. The ratio H/s must be large if the concept of an effective wall boundary condition is to have meaning. The ratio λ/s is the number of holes in one pressure gradient length scale. When this parameter is large the pressure gradient does not play an important role in the averaging process to determine the effective flow resistance. When $\lambda/s < 1$ the concept of an average boundary condition no longer has meaning since there are no longer enouch wall elements to "resolve" the structure of the applied pressure field.

The cases of a porous and a perforated lower wall were solved analytically. The porous wall solution, which corresponds to an average boundary conditon which behaves as a distributed porosity, is quite simple. The perforated wall problem was solved using an image system assuming the proportionality between pressure differential and flow rate is known for an isolated hole. Although obtaining this solution is a relatively straight forward matter, it is computationally unwieldy. Because summations over the three-dimensional image field are required, it is expensive to obtain accurate results, even if an analytical far field convection is employed to effectively reduce the number of image points required. As a result of this difficulty, the problem is now being reformulated in a way which should yield results more efficiently and in a more useful form.

From the preliminary calculations made using the image method, certain conclusions can be drawn. First, the way in which the effective wall flow resistance is obtained is different for subsonic and supersonic flow. This difference is caused by the different regions of influence for the interference effects caused by adjacent holes. Second, for a fixed perforated wall geometry the effective wall flow resistance depends on the wavelength of the wavy wall. The effect becomes more important as the wavelength becomes comparable to the hole spacing. The relative phase between the wavy wall and the hole locations also becomes important.

The reformulation of the problem involves a Fourier decomposition of the response of the perforated wall to the pressure field imposed by the wavy wall. This approach avoids, at least partially, the problems associated with the image method. It has the significant advantage that the difference between the porous and perforated wall solutions can be compared according to wave number content. This is a very important problem which will be the subject of much of the effort during the current contract year. A long term goal is to solve this problem in a transonic flow field.

Research on the Compliant Wall Wind Tunnel

Dowell has developed a simplified theoretical model for high Mach number transonic flows.[11] In other work a theory of compliant wall wind tunnels for supersonic Mach numbers has been developed.[12] In work done this past year this method of Ref. 1 has been applied to airfoils in wind tunnel environments. The classical limiting cases of rigid walls and open jets were treated first. Representative results have been obtained for a parabolic airfoil at a free stream Mach number of unity in terms of lift versus effective wind tunnel aspect ratio. Secondly, the method of Ref. 11 and the problem of Ref. 12 have been combined to develop a theory of compliant wall wind tunnels at high transonic Mach numbers.

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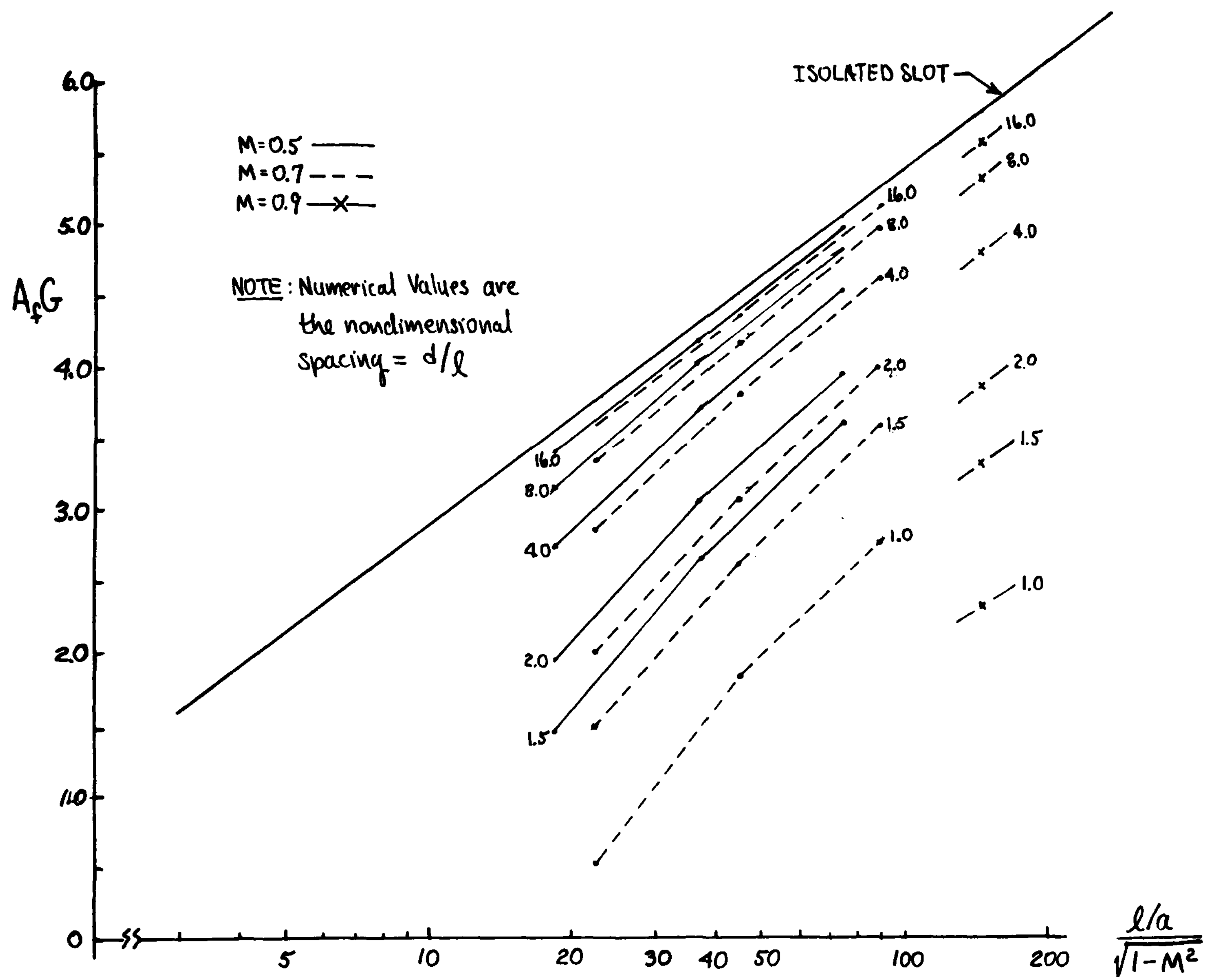

Figure 1 Effect of an Infinite Row of Slots on the Slot Flow Factor A_fG.

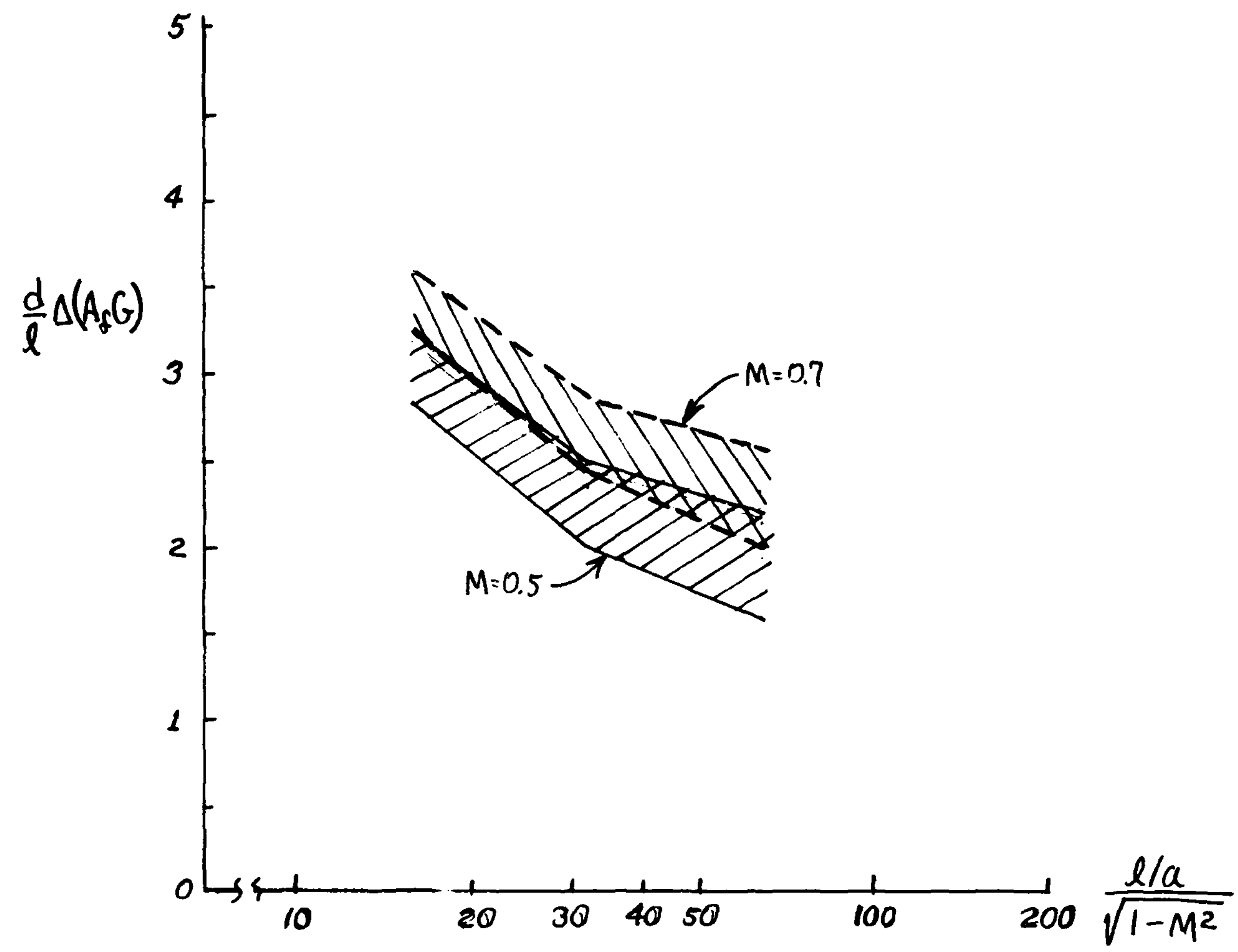

Figure 2 Change in the Slot Flow Factor, $\Delta A_f G$, Times the Slot Length to Spacing Ratio, Showing a Partial Collapse of The Computed Results.